Section Six
Treatment of Residential Duct Leakage in Title-24 Energy Efficiency Standards

Introduction

The objectives of this project were to investigate the current treatment of duct leakage and duct efficiency in the current Title-24 compliance procedures, and to uncover and evaluate alternative treatments should we find any problems with the current treatment. Our efforts can be divided into three parts: 1) a field study of duct leakage in new California houses, including development, application and verification of a simplified diagnostic procedure for duct leakage and house depressurization potential, 2) a comparison of the present treatment of duct leakage and efficiency in Title-24 compliance procedures with current research results, and 3) an analysis of the implications of alternative strategies for changing the treatment of duct leakage and efficiency in the Title-24 compliance procedures. This report documents our efforts.

Duct Leakage Field Study

A simplified duct-leakage measurement procedure was applied in 96 houses, and was compared with the results of measurements made with a direct-duct-pressurization system (i.e., Duct Blaster) in 20 of those houses. The simplified diagnostic also includes measurements of the potential for house depressurization due to the operation of exhaust fans in conjunction with the air distribution system.

Simplified Duct Leakage Diagnostic

A simplified duct-leakage measurement procedure was tested in 96 of the 100 houses visited as part of an on-site survey of whether and how those houses complied with Title-24 energy efficiency requirements. The purpose of this effort was to determine whether a very simple test for estimating the magnitude of duct leakage, one that could easily be performed by a building inspector, could be developed. This test is not intended to be a substitute for the duct-leakage measurement requirements or rewards discussed elsewhere in this document, but rather might be used to provide some level of enforcement of duct leakage requirements, or to quickly screen for houses that require duct sealing. The test may also be ideally suited to home energy ratings that already include a blower-door test of envelope leakage (see uncertainty discussion below). The original concept was that the test would ultimately require a rudimentary inexpensive pressure measurement device, and would most likely be qualitative. However, as will be discussed later, there are many advantages to using a hand-held digital manometer (There is an accurate, easy-to-use, commercially-available model which costs approximately $500), and the quantitative results proved to be surprisingly consistent with results obtained by direct duct pressurization.

The field measurement procedure evolved somewhat over the course of the project, ultimately including additional pressure measurements that would not be part of a production procedure, but which were used to help us choose appropriate assumptions in our analysis of the data. The recommended production procedure provides three outputs:

1 - an estimate of the flow from the supply ducts to outside during system-fan operation,

2 - an estimate of the flow from the outside into the return ducts during system-fan operation, and

3 - a measurement of the depressurization of the house created by exhaust fans.

The third output is not required to determine duct leakage, however it is very easy to acquire, and provides health and safety information that should be of interest to any building inspector who is performing the duct-leakage diagnostic.

The only measurement apparatus used for all of the testing performed (and which is recommended for the production procedure) was a hand-held, two-channel, digital manometer (The Energy Conservatory Digital Pressure Gauge). The measurements included in the final production protocol are:

1. Measurement of the pressure difference between the attic and the house with the **air handler fan off (ΔP_{off}),**
2. Measurement of the pressure difference between the attic and the house with the **air handler fan on (ΔP_{on}),**
3. Measurement of the pressure difference between the attic and the house with the **air handler fan on and the return grille partially blocked (ΔP_{RB}),**
4. Measurement of the pressure difference between the return duct and the house with the **air handler fan on (ΔP_{ret}),**
5. Measurement of the pressure difference between the return duct and the house with the **air handler fan on and the return grille partially blocked (ΔP_{retRB}),**
6. Measurement of the pressure difference between the attic and the house with the **air handler fan off and all kitchen and bath fans (and the dryer when inside the house) on (ΔP_{safe}),** and
7. Approximate measurement of the square footage of the house.

All three outputs are determined from these measurements by means of a simple model that is based upon a number of assumptions concerning the leakage in the building shell, and an assumption about the change in the pressure differential across supply duct leaks when the return is blocked. This latter assumption is based upon two additional measurements made in 13 of the 100 houses tested. The two additional measurements are:

1. Measurement of the pressure difference between a supply duct and the house (measured through a sealed supply register) with the **air handler fan on (ΔP_{sup}),** and
2. Measurement of the pressure difference between a supply duct and the house (measured through a sealed supply register) with the **air handler fan on and the return grille partially blocked (ΔP_{supRB}).**

These two additional measurements allow us to estimate the pressure differential across the supply leaks under both normal and blocked-return operation. As discussed below, this pressure differential varied very little as compared with the pressure differential across the return leaks, which makes it possible skip them in the production protocol.

The step-by-step production protocol is the following:

1. close all the windows and doors in the house,
2. install one plastic tube between the house and attic, passing one end of the tube through the attic access hatch, and connecting the other end to the input port of channel A of the digital manometer,
3. install a second plastic tube between the return duct and the house, passing one end through the return grille (and the filter if it is located at the grille), and connecting the other end to the input port of channel B of the digital manometer,
4. turn on the air handler fan, and record the pressure difference between the attic and the house ten times and the pressure differential between the return duct and house once (with the digital manometer in the five-second averaging mode),
5. turn off the air handler fan, and record the pressure difference between the attic and the house ten times (with the digital manometer in the five-second averaging mode),
6. turn on the air handler fan, and record the pressure difference between the attic and the house ten times and the pressure differential between the return duct and house once (with the digital manometer in the five-second averaging mode),
7. turn off the air handler fan, and record the pressure difference between the attic and the house ten times (with the digital manometer in the five-second averaging mode),
8. turn on the air handler fan, and slowly block the return grille with a piece of cardboard (it need not be taped, as the suction will even hold it up on the ceiling) until the pressure differential between the return duct and the house is approximately -100 Pa,
9. record the pressure difference between the attic and the house ten times and the pressure differential between the return duct and house once (with the digital manometer in the five-second averaging mode),
10. turn off the air handler fan, and record the pressure difference between the attic and the house ten times (with the digital manometer in the five-second averaging mode),

11. turn on all of the exhaust fans in the house (including the dryer if it is located inside the house), and record the pressure difference between the attic and the house ten times (with the digital manometer in the five-second averaging mode).

Simplified Diagnostic Uncertainty Analysis

There are several sources of uncertainty associated with the simplified diagnostic procedure described above. The sources of uncertainty include, in order of decreasing importance: 1) the uncertainty in the leakage of the building envelope, 2) the uncertainty in the pressures across the supply and return leaks during the two modes of fan-on attic pressure measurement, 3) the uncertainty associated with assuming flow exponents rather than measuring those exponents, 4) the uncertainty associated with differences in the pressure coefficients of the attic and house, combined with changes in wind speed during the test, 5) the uncertainty associated with variations in wind direction during the test, combined with non-uniformities in the leakage distribution of the house or attic, 6) errors due to inadequate attic ventilation, 7) errors due to leakage not being concentrated at the ceiling and floor (as is assumed in the derivation of the equations), and 8) uncertainties associated with the electronic pressure transducer.

Concerning the uncertainty in the leakage of the building envelope, this is the dominant source of uncertainty in the estimated duct leakage flow rates. The uncertainty in a blower-door measurement of envelope leakage is on the order of 10%, and the uncertainty associated with guessing the leakage of the building envelope in new California construction is on the order of 25%. There is some additional uncertainty associated with the fact that whoever is performing the test needs to assure that all windows and doors are closed, as an open window can easily double the leakage of the house, resulting in a false negative result for duct leakage. It should be noted that the precision of this technique also depends on the absolute level of envelope leakage, as the size of the measured pressure changes is larger for tighter houses. Thus, the technique will have the highest precision for relatively airtight houses (e.g., new construction), or for houses that have received a blower-door test of envelope leakage (e.g., for a home energy rating).

Concerning the uncertainty in the pressure differential across the duct leaks, this technique suffers from the same problem encountered by the standardized duct-leakage measurement procedures, namely that there are variations in the pressure throughout a duct system, and it is difficult if not impossible to know the pressure differential across the leaks. However, one major advantage of the simplified technique is that it makes only limited use of those pressure differentials. Specifically, the return-duct pressure is used to account for relative changes in the pressure differential across the return leaks (see Equation 3), which makes this technique relatively insensitive to the uncertainties in the pressure measurement. The other source of uncertainty in the simplified technique relative to duct-leak pressures is in the assumption made about the change in supply-leak pressures when the return is blocked. This uncertainty shows up in the constant 0.14 in Equation 3. This constant is based upon measurements made on 13 duct systems, and should be checked before embarking on wide-scale application of the technique. Alternatively, measurements of supply pressures before and after blocking the return grille can easily be added to the protocol without significantly increasing the time required for the test.

The use of assumed rather than measured flow exponents can be investigated based upon known distributions of flow exponents, by substituting the mean values used in Equations 1,2, and 3, with those plus or minus one standard deviation (approximately 14%). A limited analysis of the impact of assumed flow exponent was performed for the 100-house field-study described below. That analysis indicated that changing the assumed duct exponents by 8% changed the mean estimated leakage flows by 6%, and that changing the assumed envelope exponent changed the estimated leakage flows by less than 3%. That analysis did not examine the extra uncertainty associated with house-to-house variability in flow exponents.

Although the pressure difference between the attic and the house was chosen because the attic typically has approximately the same wind pressure coefficient as the house, both of these pressure coefficients depend on wind direction, as well as on the particular type of attic venting and the shape of the house. The uncertainty in the duct leakage results associated with this effect can be examined based upon what we know about pressure coefficients and wind speed distributions, however the uncertainty in any given measurement can be estimated by means of the standard deviations associated with each of the measured pressure differentials.

Inadequate attic ventilation could cause our estimates of duct leakage flows to be biased high, due to the fact that the flows creating the measured pressure changes in the house can also be creating pressure changes in the attic. The size of this impact can be estimated by comparing the typical leakage areas of attics with those of houses. Specifically, the nominal design value for attic leakage is 1 ft2 of open area per 150 ft2 of ceiling area, however a field study of 31 California houses of various ages found their attics to have venting of closer to 1/400 on average. Using the more conservative 1/400 number, and a house-envelope leakage value of 4 cm2/m2, an attic in a 2000 ft2, 1-story house would have 4644 cm2 of open area, versus 743 cm2/(0.6 discharge coefficient)=1238 cm2 for the building shell. This implies that the pressure differential created in the attic would be 7-13% of the pressure differential created in the house, depending upon what we assume for the flow exponent. For a two-story house with the same leakage ratios, the pressure differential in the attic would be 24-38% of that in the house. For houses with envelope leakage of 2.6 cm2/m2, as was measured for the sample reported on in this report, these percentages would be 3-7% and 10-20%, respectively. It should be noted that the magnitude of this effect is somewhat larger for older houses with leakier envelopes, as the attic leakage is likely to be closer to the house leakage in those instances. It should also be noted that the quoted attic pressures are based upon all of the duct leakage being into the attic. If all the ducts are located in a crawlspace and/or garage, attic ventilation is not important.

Concerning the impacts of envelope leakage distribution, a limited examination of the impacts of leakage distribution suggests that the results are reasonably insensitive to the assumed leakage distribution, at least for moderate changes in the assumed distribution. Specifically, assuming that 75% of the envelope leakage is in the ceiling, and that 25% is in the floor, results in duct leakage flow estimates that are 10% higher than those obtained with the assumed 50/50 distribution of envelope leakage.

Simplified Diagnostic Analysis Procedure

Our interpretation of the results of the simplified diagnostic tests is based upon a simplified model of the superposition of the pressure differential resulting from unbalanced duct leakage flow, and the pressures driving stack-induced air infiltration. The nature of this interaction depends upon: 1) the sign of the indoor-outdoor temperature differential (i.e., winter versus summer), 2) the sign of the unbalanced duct leakage flow (i.e., return-leakage versus supply-leakage dominated), and 3) the relative magnitude of the stack and duct-leakage induced pressures. The various combinations of these parameters yield six situations that need to be examined. It was found that all situations could be described with a single equation, whose derivation is included in the appendix D. The equation, based upon the assumption that half of the envelope leakage is in the ceiling and half is at the floor, is as follows:

$$Q_{sleak+rleak} = \frac{1}{2} k \times (sign\left(\Delta P_{on} - 2\Delta P_{off}\right) \times \left|\Delta P_{on} - 2\Delta P_{off}\right|^{n} + sign\left(\Delta P_{on}\right) \times \left|\Delta P_{on}\right|^{n})(Eq.1)$$

In Equation 1, $Q_{sleak+rleak}$ is the net flow leaving the house due to supply and return duct leaks, and will be presented in units of cfm, where supply leakage is defined to be positive and return leakage is defined to be negative. The pressure differentials are defined as the attic pressure minus the house pressure, where the subscripts “on” and “off” refer to the pressure differentials measured when the air-handler fan is on and off, respectively. The flow exponent, n, is dimensionless, and will be assumed to be 0.65 for the envelope leaks that come into these calculations. The flow coefficient for the house, k, has the units of cfm/ Pa^{n}.

The supply and return duct leakage flows that make up the unbalanced flow determined with Equation 1 are computed by combining the normal-system-operation results with the blocked-return test results. Applying the same principles and assumptions, the unbalanced duct leakage flow under blocked-return conditions are computed using Equation 2:

$$Q_{sleak+rleakRB} = \frac{1}{2} k \times (sign\left(\Delta P_{RB} - 2\Delta P_{off}\right) \times \left|\Delta P_{RB} - 2\Delta P_{off}\right|^{n} + sign\left(\Delta P_{RB}\right) \times \left|\Delta P_{RB}\right|^{n})(Eq.2)$$

By measuring the change in the pressure differentials across the supply and return leaks associated with blocking the return grille, the difference between the unbalanced flows calculated with Equations 1 and 2 can be used to estimate the supply and return duct leakage flows under normal operating conditions. As the change in the pressure differential across the supply leaks associated with blocking the return grille was found to be much less than the change in the pressure differential across the return leaks, the production protocol does not include measurements of supply duct leakage pressures. Based upon the supply-duct pressure differentials measured in 13 houses, the supply-duct pressure differential was found to decrease by an average of 22% when the return was blocked, with a standard deviation of 10 percentage points. By comparison, the median increase in the return-duct pressure differential was almost 600%, with a standard deviation of 800 percentage points. Incorporating the average change in the supply-leakage pressure differential, and thus the supply-side leakage flow into the equations yields Equations 3 and 4 for the supply and return duct leakage flows under normal operating conditions.

$$Q_{sleak} = \frac{Q_{sleak+rleak} - \dfrac{\left|\Delta P_{ret}\right|^n}{\left|\Delta P_{retRB}\right|^n - \left|\Delta P_{ret}\right|^n} \times \left(Q_{sleak+rleakRB} - Q_{sleak+rleak}\right)}{1 + 0.14 \dfrac{\left|\Delta P_{ret}\right|^n}{\left|\Delta P_{retRB}\right|^n - \left|\Delta P_{ret}\right|^n}} (Eq.3)$$

$$Q_{rleak} = Q_{sleak+rleak} - Q_{sleak} \, (Eq.4)$$

The flow exponent in Equations 3 and 4 is that of the duct leaks, which is assumed to be 0.6 in the results presented below. The constant 0.14 in Equation 3 is dimensionless, and represents the average fractional change in supply duct leakage flow when the return grille was blocked in this study. The general expression from which 0.14 was derived is $(1-(\Delta P_{supRB}/\Delta P_{supon})^n)$. This expression should be used instead of 0.14 if the supply-side pressures are available.

Another equation required for the data analysis is one that estimates the leakage of the building shell from the floor area:

$$k\left[\frac{cfm}{Pa^n}\right] = 0.053 \times \left(floorarea\left[ft^2\right]\right)(Eq.5)$$

The constant in Equation 5 is based upon the envelope-only leakage results obtained in the twenty houses measured as part of this study. When applying these analysis equations it is always preferable to use measured envelope leakage, however for the very uniform sample of houses measured in this study, the specific envelope leakage area was 2.6 cm2/m2 (see envelope leakage data and discussion below).

The equations presented above are based on the assumption that leakage in the duct system does not significantly impact the vertical distribution of leakage in the building shell, or in other words that the duct leakage not does affect the height of the neutral level, which is assumed to be at the center of the building. However, if all (or the vast majority) of the duct leakage is located in the attic, and that duct leakage represents a significant fraction of the total building leakage, both of which are true in this study, the results obtained with Equations 1 through 5 need to be corrected for the shift in neutral level associated with turning on the distribution system fan. The correction, which should be applied to Equations 1 and 2 (or to Equations 3 and 4 if the intermediate results are not of interest) is derived in the appendix D for a number of assumptions about the distribution of leakage in the envelope. A general approximate equation for estimating the correction factor for attic-only duct leaks is:

$$C_{nl} = \left(\frac{1 + (2x+1)^{1/n}}{2} \right)^{n} \quad (Eq.6)$$

where x is the ratio of the attic-only duct leakage to the envelope duct leakage.

Some typical correction factors based upon Equation 6 are summarized in Table 6-1.

Table 6-1
Duct Leakage-Flow Correction Factors Based on Equation 6

Configuration	Envelope Leakage [cm2/m2]	Duct Leakage [cm2/m2]	Correction Factor [-]
Attic Only Duct Leaks	2.55	0.84	1.35
Attic-Only Duct Leaks	4	1	1.26
Attic-Only Duct Leaks	6	1	1.17

The correction factors in Table 6-1 should only be applied if the duct leakage is entirely in the attic. If the duct leakage is split equally between the attic and crawlspace, then there is no need for a correction factor. If the duct leakage was entirely in the crawlspace the correction goes in the other direction.

Simplified Diagnostic Test Results

The results of the simplified diagnostic tests on 96 houses are presented in this section. The principal results, namely the estimated unbalanced duct leakage flow, and the estimated supply and return duct leakage flows making up that unbalanced flow, are presented first, followed by the measurement results for whole-house depressurization. Highlights of the supply-minus-return leakage flow results, the supply-leakage flow results, and the return-leakage flow results obtained with the simplified diagnostic procedure are summarized in Table 6-2.

Table 6-2 provides a fairly clear picture of the leakage characteristics of the duct systems in the 96 houses examined. First, it is evident from the results in Table 6-2 that there is significant air distribution system leakage in many of these houses. More than a quarter of the return systems have more than 100 cfm of return-duct leakage from outside, and 40% of the supply-duct systems have more than 100 cfm of leakage to outside. These results suggest that there is actually somewhat more supply leakage than return leakage, whereas previous studies indicated somewhat more return leakage. More significantly, these results clearly indicate non-zero return leakage to outside, whereas it was assumed in the 1988 Title-24 compliance algorithms that there are no return leaks to outside.

Table 6-2
Summary of Duct Leakage Flow Rates Estimated with Simplified Diagnostic Protocol[a] (96 Houses)

DESCRIPTION	ABSOLUTE VALUE OF UNBALANCED DUCT LEAKAGE FLOW	SUPPLY-DUCT LEAKAGE FLOW	RETURN-DUCT LEAKAGE FLOW
Average Flow [cfm]	92	86	69
Maximum Flow [cfm]	482	503	375
Number >100 cfm	33	38	24
Number 0-25 cfm	24	40	37
Number 25-50 cfm	10	5	17
Number 50-100 cfm	29	13	18
Number 100-200 cfm	20	26	15
Number >200 cfm	13	12	9

[a] using 2.6 cm^2/m^2 for envelope leakage, and constant 1.35 correction factor for fan-induced neutral-level shift

It is important to note that a number of apparent failures of the analysis equations were uncovered as part of the data reduction used to obtain the results in Table 6-2. Specifically, negative supply-duct leakage flows were obtained in 21 cases. Of these, four cases were due to clearly odd data, and the 17 others were from houses which had little or no supply leakage. In most of the 17 cases the negative signs were on very small leakage flows, which could be explained by poor signal to noise. In five houses, the equations came up with large negative supply leakage flows. All five were for duct systems with very large return leakage flows that resulted in large changes in house pressure. With such large leakage flows, there is a much higher probability of non-uniform pressures across the duct leaks, and the extrapolation errors due to exponent uncertainties are likely to be larger. In each of those five houses, it was found that adding the negative supply leakage flows to the return leakage flows yielded the correct unbalanced leakage flows under normal operating conditions, which were used as the estimates of the return leakage flow, with the supply leakage flow set to zero.

The assumed envelope leakage in Table 6-2 is based upon the blower-tests of envelope leakage in this study, which indicated significantly tighter envelopes as compared to earlier studies. More specifically, the average specific leakage area for the 20 houses that were submitted to blower-door tests was 3.4 cm^2/m^2, which when the average duct leakage of 0.8 cm^2/m^2 is subtracted yields an SLA for the envelope of only 2.6 cm^2/m^2. If the envelopes are not this tight, then the estimated duct leakage flow rates would be higher.

If the envelopes in new California houses are in fact as tight as indicated in this study, there are some interesting implications for ventilation in California residences. A tightness level of 2.6 cm^2/m^2 is only 70% higher than the Swedish air leakage standard, and most new houses in Sweden get mechanical ventilation systems, even with the much larger driving forces for infiltration in Sweden as compared to California. The measured duct and envelope leakage results are compared with those from other sources in Table 6-3. It is also worth noting that as the envelopes in California houses are getting tighter and tighter, the duct systems do not seem to be improving significantly. Moreover, the apparent improvement in the two CEC studies may not be real, as the 0.9 number is most likely biased low due to the measurement technique employed (blower-door subtraction is typically biased low by ~30%), and the 0.8 number may be due to the fact that the duct systems are almost brand new, and the duct tape has not yet begun to fail. It should be noted that if the 0.9 number is biased low, then the 3.9 number from that study is biased high.

Table 6-3
Comparison of Envelope and Duct Leakage Levels From Different Sources

California House Vintage [reference]	**Specific Leakage Area [cm^2/m^2 floor area]**	
	Envelope	**Ducts**
Pre-1980 [Modera 1993]	6.0	1.0
1980-1990 [Modera 1993]	3.9	1.0
1984-1988 [CEC P400-90-009]	3.9	0.9
1993-1994 [CEC 400-91-031]	2.6	0.8
SWEDISH STANDARD	1.5	N/A

Pressure Safety Results

The impacts of duct systems and exhaust fans on the potential depressurization of the house (associated with the possibility of combustion appliance spillage or backdrafting) was measured for two modes of operation, and calculated for a third. The first mode of operation is with the air-handler fan on and all exhaust fans off. This is measured automatically as part of the data required to estimate duct leakage flows. The second mode of operation is with the air handler fan off, and all kitchen and bath exhaust fans on (including the dryer if it was inside the conditioned space). This is the final pressure measurement associated with the production protocol.

The third mode of operation, with the air handler fan on and all exhaust fans on, was not measured (see discussion below concerning adding this measurement to the protocol). The house depressurization associated with this mode of operation was calculated by assuming that the flows through the building shell associated with both the air handler and the exhaust fans are passing through all of the building leaks, and thus that the flows can be added so as to compute a total flow, and thus a total pressure differential. These assumptions yield Equation 7, which is used to calculate the combined air-handler/exhaust-fan results in Table 6-4. The assumption that the pressure differentials associated with both air-handler and exhaust flows are due to flow through all of the envelope leaks should be true whenever those two flows are large (i.e., in situations where the depressurization is large enough to be of interest). The flow exponent to be used in Equation 7 is that for the building envelope, and thus 0.65 was used for the results in Table 6-4.

$$\Delta P_{exfan+airhand} = sign\left(\Delta P_{exfan} + \Delta P_{on-off}\right) \times \left| sign(\Delta P_{exfan}) \times \left|\Delta P_{exfan}\right|^{n} + sign\left(\Delta P_{on-off}\right) \times \left|\Delta P_{on-off}\right|^{n} \right|^{\frac{1}{n}}$$

(Eq.7)

Table 6-4
Whole-House Depressurization Associated with Three Modes of Operation (88 Houses)

DESCRIPTION	AIR HANDLER OPERATION ONLY (MEASURED)	EXHAUST FAN OPERATION ONLY (MEASURED)	AIR HANDLER AND EXHAUST FAN OPERATION (CALCULATED)
Average Depressurization [Pa]	0	3.0	3.5
Median Depressurization [Pa]	0.1	2.4	3.1
Maximum Depressurization [Pa]	3.8	11.7	14.5
Number > 10 Pa	0	1	5
Number 7.5-10 Pa	0	2	9
Number 5-7.5 Pa	0	8	12
Number 3-5 Pa	2	27	19

The results in Table 6-4 indicate that approximately 30% of the houses have the potential to be depressurized by more than 5 Pa, and that 6% of the homes have the possibility of being depressurized by more than 10 Pa. These are interesting results, as the possibility of backdrafting combustion appliances starts at approximately 3 Pa, is worthy of concern above 5 Pa, and is relatively likely above 10 Pa [Nagda et al. 1995, Scanada 1988]. In addition, it has been suggested that depressurization exceeding 12.5 Pa can result in flame roll-out from water heaters.

Although it is clear that these results merit further investigation, we need to remember that the probability for disaster is not in the range of 6-30%. The probability of having a combustion backdrafting problem is equal to the product of the probabilities of: 1) having enough exhaust appliances and a tight enough building envelope to create a level of depressurization that can cause backdrafting (the 6-30% numbers quoted above), 2) having enough of those exhaust appliances on at the same time, 3) simultaneously having a combustion appliance that can be backdrafted in operation, and 4) having that combustion appliance create enough CO to be of concern (It should be noted that the rate of CO production can change when an appliance is backdrafting.) Nevertheless, these results suggest that some attention be given to the issue of combustion safety in new California construction.

Simplified-Diagnostic/Duct-Blaster Comparison

Twenty of the houses submitted to the simplified duct diagnostic protocol also received duct-blaster measurements of duct leakage. These measurements included:

1. A measurement of total duct-system leakage with the duct blaster,
2. A measurement of total duct-system leakage to outside with a duct blaster, and
3. A measurement of the split between supply-side and return-side duct leakage.

These duct-blaster tests are not measuring the same thing as the simplified diagnostic procedure, however they can still be used to provide a check of whether the simplified diagnostic results are reasonable. The two sets of results cannot be compared directly because the simplified diagnostic procedure is estimating the duct-leakage flows to outside under normal operating conditions, whereas the duct blaster tests are measuring the total duct-leakage flows under specified pressure conditions. However, the duct-leakage flows under normal operation can be estimated from: a) the leakage coefficients obtained with the duct blaster, and b) the pressures across those leaks during normal operation. The complete set of data required for this comparison is available only for the return-side leakage flows. Thus, the return leakage flow rates measured under normal operation with the simplified duct diagnostic are compared with those obtained from the duct blaster results and measured operating pressures in Figures 6-1 and 6-2. The diagnostic results in Figure 6-1 use the measured envelope leakage area for each house for the purposes of this comparison, and the results in Figure 6-2 are based upon multiplying the floor area of the house by an assumed Specific Leakage Area (SLA) of 2.6 $cm^2/(m^2$ floor area), which is the average measured leakage area of the envelopes of the 20 houses tested. The measured envelope leakage areas are obtained by subtracting the duct leakage area measured with the duct blaster from the total building leakage area (ducts plus envelope) measured with the blower door. Although using the measured leakage areas (Figure 6-1) improved the correlation between the simplified diagnostic and duct blaster results, the results based upon estimated envelope leakage (Figure 6-2) remain acceptable. In both cases an average correction factor of 1.35 was used to account for the fact that the vast majority of the duct leakage is in the attic. The value 1.35 is based upon the average measured envelope and duct leakage values (2.6 cm^2/m^2 for the envelope, 0.84 cm^2/m^2 for the ducts). Linear regressions to the data in Figures 6-1 and 6-2 yield slopes of 0.88 and 0.96 respectively, and intercepts of 9.6 cfm and 8.4 cfm respectively.

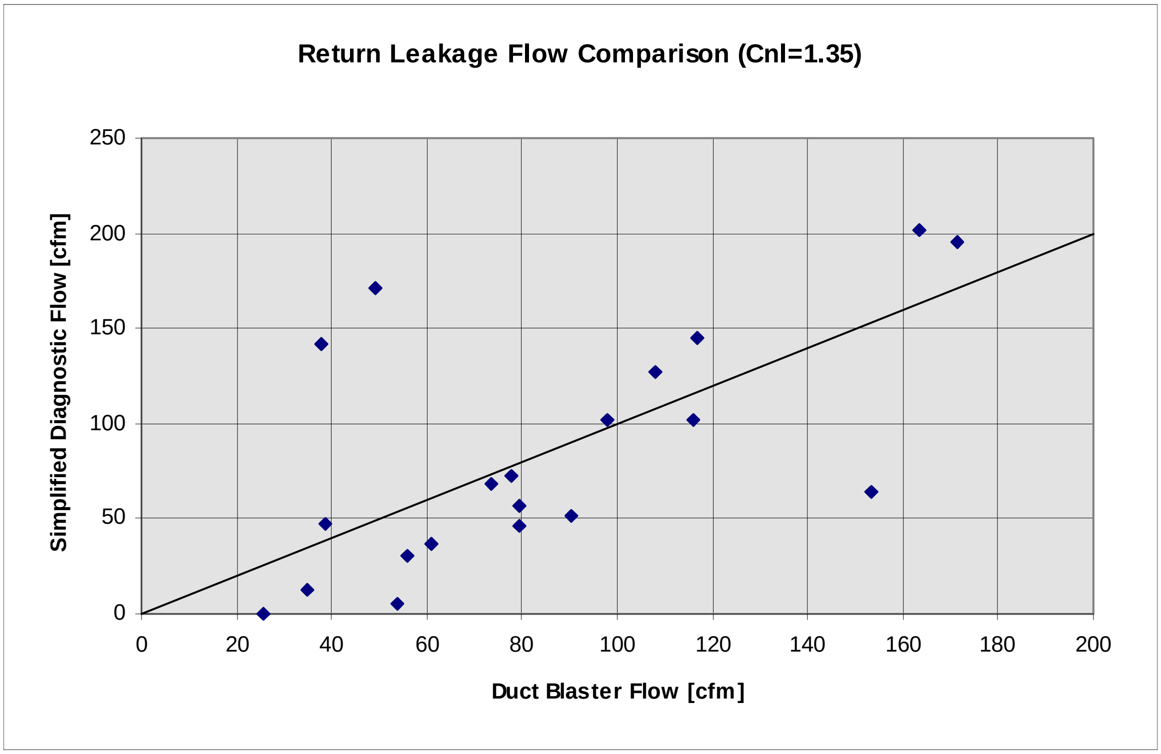

Figure 6-1
Comparison of Return Leakage Flows - Duct Blaster versus Simplified Diagnostic Procedure (using measured envelope-only leakage, constant 1.35 correction factor for neutral-level shift due to attic duct leakage).

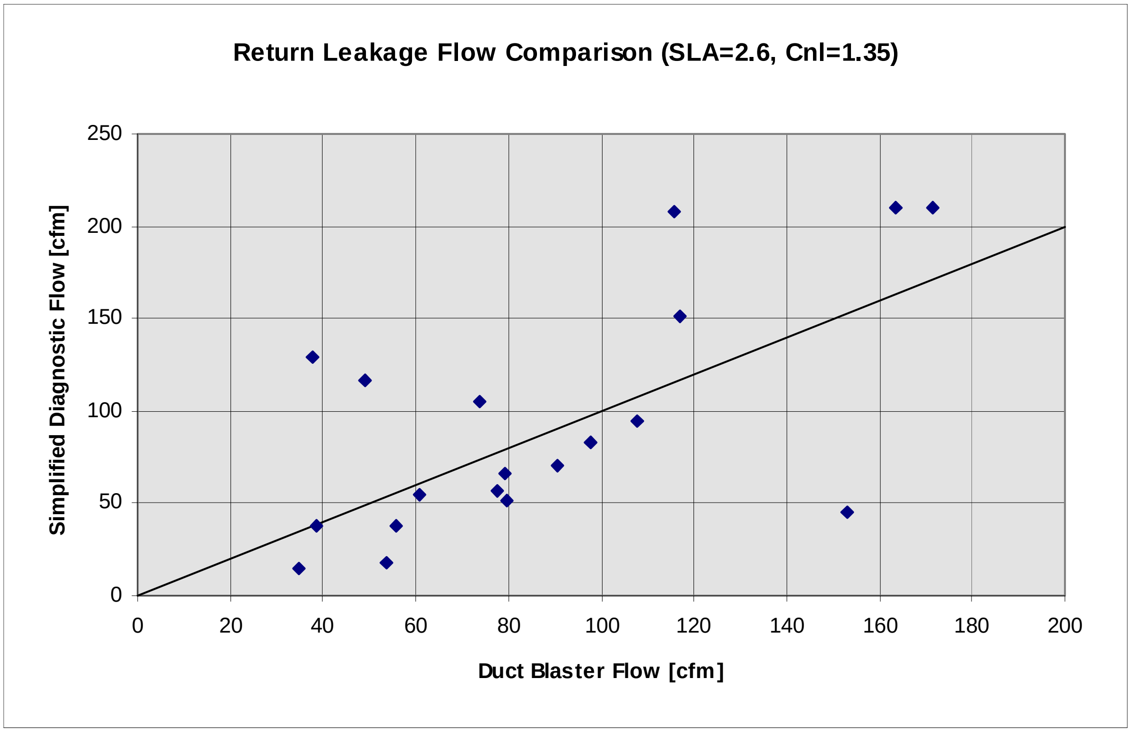

Figure 6-2
Comparison of Return Leakage Flows - Duct Blaster versus Simplified Diagnostic Procedure (using envelope leakage based upon floor area and SLA of 2.6 cm^2/m^2, constant 1.35 correction factor for neutral-level shift due to attic duct leakage).

The results presented in Figures 6-1 and 6-2 are encouraging. Except for three outliers, there is good agreement between the flows obtained with the simplified diagnostic, and those obtained with the duct blaster. There is a reasonably clear linear relationship between the two sets of results, although the simplified diagnostic results appear to be slightly negatively biased when the outliers are excluded. This negative bias may be due to the fact that some of the leakage estimated with the duct blaster technique may not be going outside, whereas the simplified diagnostic measures only leakage to outside.

No clean explanation for the outliers in Figures 6-1 and 6-2 was uncovered, however two potential causes were uncovered: 1) two of the outliers were from data sets for which the duct blaster data had to be corrected for a missing measurement based upon some assumptions about the characteristics of the duct system, and 2) the duct blaster leakage flows are based upon assuming that the ducts are submitted to the pressure differential measured at the return grille, which may not be accurate.

The data acquired to analyze the performance of the simplified duct leakage protocol is of interest in its own right. In particular, the envelope and duct leakage data confirm trends seen in earlier field studies, and envelope leakage suggests that new California envelope construction is quite airtight, perhaps too airtight to provide adequate ventilation. The envelope and duct leakage measurements from our present field study are compared with data from previous studies in Table 6-3, and are summarized statistically in Table 6-5.

Table 6-5
Summary of Leakage Measurement Results
[Specific Leakage Area cm^2/m^2 floor area or in^2 10,000 in^2 floor area]

Leakage Site	Average	Standard Deviation [%]	Maximum	Minimum
Total	3.4	21%	5.0	2.4
Duct	0.84	48%	1.7	0.2
Envelope	2.5	32%	3.8	0.8

Duct Treatment in Current Title 24 Standards

General. The numbers used for duct system efficiencies in the current Title-24 compliance tools are based upon a relatively simple model of duct efficiency that takes into account conduction losses/gains and air leakage for supply ducts. Since the time when that algorithm was developed, a fair quantity of research has been performed, including the development of more sophisticated models of duct system performance, and field studies of duct system performance. The general conclusion that can be reached based upon a comparison of the results of current research with the present numbers and algorithms for duct efficiency in the Title-24 Standards is that the Title-24 model results in duct-system efficiencies that are too high. Table 6-6 presents a comparison of the Title-24 numbers with those based upon current research for attic duct systems with R-4 insulation.

Several clarifications relative to Table 6-6 need to be made. First, the Title-24 model calculates a delivery efficiency, and uses that efficiency as the overall duct-system efficiency, whereas the Treidler et al. [1995], and Jansky and Modera [1993] calculate overall duct-system efficiency. The Olson et al. [1994] study measured both delivery and overall duct-system efficiencies, the latter with electric co-heating. The efficiencies from the Olson et al. [1994] study are for duct systems with R-8.6 insulation on average in the Pacific Northwest in the winter. The Walker and Jump delivery efficiencies are based upon a personal communication, and are for California houses built predominantly after 1977. The major difference between the Treidler et al. and Jansky/Modera results are primarily due to the surface areas of the duct systems simulated, 27% versus 44% of house floor area (see Table 6-7), respectively, and somewhat due to changes in the specified system air flow rates, modeling of duct dynamics, and modeling of thermosiphon losses.

Table 6-6
Comparison of Duct-System Efficiencies

Source	Duct Efficiency (Cooling) [%]	Duct Efficiency (Heating) [%]
1988 Title-24 (Model)	82	81
Treidler et al. 1995 (Model)	72	72
Jansky and Modera 1993 (Model)	64	61
Olson et al. 1994 (Measurement in 24 houses)	71 (56 Delivery)	N/A
Walker and Jump 1995 (Measurements in 17 houses)	~63 Delivery	

Several reasons were identified for why the current Title-24 duct efficiency number are high relative to all of the current studies examined. First, the surface area assumed in the Title-24 numbers are much lower than those assumed in the other studies, and measured in the field (see Table 6-7). Second, the Title-24 algorithm assumes that there are no return-system leakage or conduction losses. Third, the efficiencies in the Title-24 algorithm do not account for off-cycle losses due to the duct system. Of the two types of off-cycle losses, the Title-24 standard may implicitly account for the off-cycle infiltration load due to duct leakage by including duct leakage in the assumed envelope leakage, however this was not confirmed. On the other hand, the effect of thermosiphon-induced heat losses is certainly not included in the Title-24 algorithm systems (approximately a 2-4 percentage-point effect). Fourth, the Title-24 algorithm does not account for any dynamic losses from the duct systems (approximately a 1-2 percentage-point effect).

Table 6-7
Comparison of Duct System Surface Areas

Source	Duct System Surface Area in 1-Story House [% of House Floor Area]	Duct System Surface Area in 2-Story House [% of House Floor Area]
1988 Title-24 (Model)	15	8
Treidler et al. 1995 (Model)	27	13
Jansky and Modera 1993 (Model)	44	N/A
Walker and Jump 1995 (Measurements in 18 Post-1977 California Houses)	24	13

Another important issue relative to the Title-24 algorithm for duct efficiency is the fact that it does not account for the interactions between duct systems and HVAC equipment. In general, inefficient ducts generally increase equipment efficiency to some extent by reducing cycling losses, however there are two important exceptions to this trend. First, inefficient ducts tend to increase the use of electric resistance back-up on heat-pump systems. This is due to the increased loads created by the of duct systems, and has been confirmed experimentally [Modera and Jump 1995]. A similar decrease in equipment efficiency is seen for two-speed air conditioners [Modera and Treidler 1995]. This second effect should be of particular concern for the Title-24 standards, as they include credits for higher-efficiency equipment (into which category two-speed compressors normally fall), and the modeling results suggest that only about half of the expected energy savings is seen with this equipment.

One final note relative to duct system efficiency in Title-24 concerns duct insulation. A recent study by Lawrence Berkeley Laboratory and Pacific Northwest Laboratory indicates that duct insulation levels of R-8 should be cost-effective for supply ducts in attics in new construction in California [Treidler et al. 1995].

Air Leakage. As noted above, the present treatment of duct leakage in the Title-24 compliance procedures assumes that there is no return-duct leakage. The results of the simplified duct-diagnostic tests clearly show that this not accurate for new California construction, consistent with earlier studies which measured significant return leakage in California houses [Modera 1993, Modera and Jump 1995]. The diagnostic field-test results indicated return-duct leakage flows under normal operating conditions of 69 cfm on average if the envelope leakage is assumed to be 2.6 cm^2/m^2 .

Depending upon which level of envelope leakage is assumed, the supply leakage flows assumed in the current Title-24 compliance procedures may be very reasonable. The average supply leakage for, our sample is 86 cfm, which is very close to the average that would be obtained from the current Title-24 algorithm for the 60/40 split of one-story and two-story houses in the diagnostic field-test sample (0.6*108+0.4*72=94).

One final point relative to the treatment of duct leakage in the current compliance procedure is that the procedure seems to use too low of a duct-system pressure for heat pumps. More specifically, the current procedure assumes that the pressure differentials across the duct leaks are lower for heating than for cooling. This makes sense for gas furnaces, which operate at lower fan speeds than air conditioners, however this is generally not the case for heat pumps. This effect was not well documented, so it would be fruitful to check this once again in the algorithm.

Duct Leakage Issues for New California Homes

There are a number of issues associated with choosing an appropriate strategy for reducing duct leakage in residential construction, as well as with choosing the appropriate level of that leakage reduction. In developing a strategy, there are several questions that need to be answered: 1) what is the typical leakage level of duct systems in new California residences? 2) what is the energy penalty of that leakage? 3) what are the practical cost-effective alternatives for reducing that leakage? 4) how can tighter duct leakage standards be enforced? and 5) how should tighter duct leakage standards be incorporated into the present structure of the Title-24 compliance procedure?

The data taken in the 100 site visits provides us with information that can be used to choose an effective strategy, including: a) a reasonable picture of duct leakage characteristics in new California construction, b) a verified procedure for simply enforcing duct leakage standards, and c) a health and safety impetus for building inspectors to care about duct leakage as well as exhaust fan safety issues.

Level of Duct Leakage in New California Residences. A large number of field measurements of residential duct leakage have been conducted over the past five years [Cummings 1990, Davis 1993, Modera 1993, Olson et al. 1994, Proctor 1990, Proctor et al. 1990, Proctor and Pernick. 1992]. Three pertinent conclusions can be drawn from these measurements: 1) average duct leakage levels are surprisingly consistent across the regions of the country in which ducts are installed in attics and crawlspaces, 2) there is large house-to-house variability in the leakage levels measured, and 3) duct-system air tightness has not apparently improved as a result of the Title-24 energy standards [Modera 1993].

The duct-leakage results obtained from the 20 site visits that received duct-blaster tests of leakage are consistent with all three conclusions from the earlier studies. The specific leakage area of the 20 duct systems tested with the duct blaster was 0.84 cm^2/m^2 of house floor area, which is slightly lower than the average value of approximately 1 cm^2/m^2 from all the other field studies. To investigate whether these 20 houses were representative of the remaining 80 houses, the return leakage flows measured for the 20-house subset of the site visits can be compared with those obtained for the full 100 houses. This comparison shows reasonable consistency between the two data sets. The 100-house sample yields a mean return-leakage flow of 69 cfm with a standard deviation of 120%, whereas the 20-house subset yields a mean return-leakage flow based on the simplified diagnostic of 84 cfm with a standard deviation of 74%. Thus, the leakage areas measured with the duct blaster on the 20 houses are reasonably likely to be consistent with those that would have been measured for the full 100 houses (the two means differ by slightly more than one standard error in the mean of the 20-house sample). If anything, the 100-home sample is likely to have somewhat less duct leakage than the 20-house sample.

Energy Impacts of Duct Leakage in New California Residences. The energy impacts of the observed leakage levels in the new houses tested can be estimated several ways, including: 1) comparison with the results of a sensitivity analysis performed with a detailed computer model by Lawrence Berkeley Laboratory [Jansky and Modera 1993], or 2) using the model of duct efficiency in the current Title-24 compliance procedure including the impact of return leakage and appropriate corrections for the other unmodeled effects. In general, the savings associated with going from typical duct leakage levels to the levels that have been shown to be practical in North Carolina and Florida should save approximately 10% of the annual HVAC energy consumption [Jansky and Modera 1993, Treidler et al. 1995].

Enforcement of Duct Leakage Requirements for New California Houses. The data obtained with the simplified diagnostic protocol suggests that this protocol could serve as a relatively straightforward means for enforcing requirements for tighter duct systems. This protocol takes approximately 10 minutes to complete, and requires one rugged $500 piece of equipment. Moreover, the training required to perform this test is minimal. Two non-technical undergraduate students performed all of the measurements reported for the 100 houses, both of whom were able to learn the procedure based upon a one-time demonstration and a one-hour lecture. The other important characteristic of this protocol is that it not only provides information on duct-system tightness, but also on pressure safety problems. This latter characteristic should get the attention of building inspectors whose limited available time at the job site is by necessity dominated by health and safety concerns.

Rewarding Reduced Duct Leakage in the Present Title-24 Compliance Procedure. There are a number issues associated with incorporating tighter duct leakage standards into the current Title-24 compliance procedure. The first point to be raised relative to this is that the present simulation tool used for Title-24 compliance assumes duct efficiencies that are much higher than those being measured in the field, principally due to assuming unrealistic duct leakage levels. This leaves very little room for builders or contractors to improve the performance of the duct systems being installed. Thus, the first step towards improving duct efficiencies in California houses should be to change the default duct efficiencies within the code compliance tools to realistic values. There is enough existing data to defend such a change, and realistic duct efficiencies provide much-needed room for duct-efficiency improvement within the standards. In addition, combining this change with an appropriate default efficiency for conditioned-space ductwork will provide a strong encouragement for such systems in the marketplace.

It should be noted that changing the default duct efficiencies in the compliance tools by itself will not save any energy, as it will increase the predicted energy budget of the base-case house as well as the predicted energy budgets of the houses being built. On the other hand, if the energy budget of the base-case house is kept constant, the energy savings should be significant. One potential impediment to choosing default duct efficiencies that include duct leakage is that the default leakage level used to compute these efficiencies may change with time, should the industry start to do a better or worse job on duct sealing for whatever reason. Existing data [Modera 1993] has not indicated any such trend, however this possibility would have to be taken into account if the changes in default efficiencies is accompanied by prescriptive requirements for duct sealing. To accommodate this possibility, default duct leakage levels, and therefore default duct efficiency levels, should be updated on a regular basis. On the other hand, assuming that duct leakage levels do not increase, the onus of proving changes (in this case reductions) in duct leakage will not rest on the CEC.

Strategies to Reduce Duct Leakage in New California Homes

The issue of how to change the Title-24 standards so as to effect real energy savings within the state requires considerable discussion. There are four primary options for change in the standards relative to duct leakage. These four options are: 1) to require duct leakage testing, along with a limited number of prescriptive requirements, 2) to add a detailed set of prescriptive requirements to the standard, 3) to provide rewards within the standard for a combination of performance testing and a limited set of prescriptive requirements, and 4) to provide rewards within the standard for following a detailed set of prescriptive requirements. These options are presented in order of decreasing magnitude and probability of effecting actual energy savings within the state. It should be noted that for all four options, an alternative pathway to compliance or reward is to locate ducts entirely within the conditioned space, in which case many of the measurement and prescriptive requirements can be relaxed.

Combined Measurement and Prescriptive Requirements. The first option, that of specifying required leakage levels verified by measurement in all new houses, combined with some prescriptive limitations on the materials and techniques used to achieve these leakage levels, will definitely result in significant energy savings for the state of California. This option, which is supported by most of the researchers in residential duct systems, is based on the philosophy that duct systems should be treated in the same way as natural gas or water piping systems. A defensible parallel with the health and safety rationale for gas-line leak testing can be made. The argument goes along the lines that duct leaks can, and often do, create unwanted pressures and air flows within the building, such as depressurization and potential back-drafting of combustion appliances, as well as intake of undesirable gases such as automotive exhaust gases or paint/solvent fumes from garages, and/or soil gases (including moisture, radon, termaticides, and bioaerosols) from crawlspaces. The data acquired in the 100 site visits confirms the possibility of backdrafting combustion appliances.

This first option will, barring the argument that it will increase house prices and thereby reduce housing starts, result in the creation of a significant number of jobs in California. Moreover, if one believes that housing starts would be reduced by a cost increase of $100-300, it should be noted that we expect the costs of sealing and testing to be partially or completely offset by downsizing cooling and heating equipment. A detailed sensitivity analysis of duct insulation levels confirms this hypothesis [Treidler et al. 1995], as does field experience with duct leakage sealing programs in North Carolina and Florida. The experience in North Carolina and Florida has been that contractors, after having been trained, have been constructing essentially airtight duct systems without any incentives from utilities. The present duct leakage protocol for new construction being promoted in North Carolina is included in the appendix E. The creation of jobs in California results from the fact that duct sealing is at present a labor-intensive on-site activity. Thus, the consumers HVAC dollars would be spent on the labor of California HVAC contractors rather than on purchasing oversized heating and cooling equipment that needs to be imported into the state.

Two other potential points of contention associated with option 1 are the timing and the certification of leakage testing. Developments over the past several years suggest that these issues can be resolved in a fairly straight-forward manner. Concerning the timing issue, which is that ducts should be tested and sealed while they are still accessible, it should be noted that a study in 1990 demonstrated the ease and effectiveness of testing and sealing ducts at the rough-framing stage of construction [Modera 1990]. Relatively inexpensive devices (~$1000-1500) for accurately measuring residential duct leakage and guiding sealing of those leaks at the rough-framing stage have been on the market for the past several years. Concerning the issue of certification, several groups are successfully marketing training courses to HVAC contractors for testing and sealing leakage in residential duct systems. The Florida Solar Energy Center course has graduated 400 attendees, and the North Carolina Alternative Energy Center course has 200 graduates. Moreover, the rule of thumb in North Carolina has been that contractors consistently meet a leakage specification (20% of typical leakage levels) by the time they do their third house. The apparent rule of thumb in Florida is that contractors don’t fail the post-construction leakage test more than once.

The principal reason for adding prescriptive duct-sealing requirements to the measurement requirements in option 1 is to help insure the longevity of the seals. For example, the state of Florida essentially precluded the use of standard “duct” tapes, due to their known quality control and longevity problems (see copy of Florida code in the appendix F). Unpublished data from a comparative study in Florida of houses whose ducts had been sealed with duct tape, and those sealed with mastic showed a large number of duct tape failures, and relatively few failures of mastic seals (personal communication with Jim Cummings of the Florida Solar Energy Center).

Underwriter’s Laboratories (UL) has developed sealant standards (U.L. 181A for rigid duct tapes), and is continuing to develop standards for tapes (U.L. 181B for flexible ducts) that could be incorporated into the CEC requirements. It should be noted that most duct-leakage researchers believe that mastics are still the only way to go. U.L. is apparently very close (i.e. by this summer) to having in place a certification standard for flexible-duct tapes (U.L. 181B) and mastics (U.L. 181BM). The passage of the UL certification standard may be a prerequisite for including mastics in the California Title-24 Standard, as there were problems with building code officials red-tagging ducts sealed with mastic because the mastic certification standard was not on the books. Florida has temporarily put the mastic specifications on hold until the U.L. certification becomes official.

Another recent development which can serve as a precedent for prescriptive duct sealing requirements in California is that at the last Council of American Building Officials (CABO) Model Energy Code (MEC) meeting, the following language was approved:

503.10.2 Duct Sealing: *All low pressure supply and return ducts shall be sealed using mastic with fibrous backing tape installed according to the manufacturer's specifications. Other sealants may be approved by the building official. For fibrous ducts, pressure-sensitive tape may be used if installed in accordance with RS-45.* ***Duct tape is not permitted as a sealant on any ducts.***

Prescriptive-Only Requirements. The second option, a detailed list of prescriptive requirements for residential duct systems, is also likely to result in energy savings for the state of California. The level of savings to be expected clearly depends on the strictness of the prescriptive requirements, however the savings are not likely to be as large as those obtained with performance measurement requirements. On the other hand, this type of requirement is more familiar, and generally more accepted by the building community. The prime example to be drawn upon in the residential duct arena is the Florida Energy Code, which has included progressively stricter and more detailed requirements for residential duct construction over the past four years. As Florida home and duct-system construction is similar to that in California, such an approach could be adopted word-by-word, or could be used as the basis for a California version that accommodates our state's particular standards history and political environment. It is worth noting that the state of Florida has not performed any systematic studies of the impact of the standard on residential duct leakage levels, however there are some pre- and post-standard measurements available, as well as an increasing quantity of anecdotal evidence of leakage reduction as a result of the standard. Another issue worth noting relative to this option is that the enforcement may be more complex than that associated with an inspector looking for a measured leakage certification (option one). Specifically, the building inspector would have to both spend more time learning about the detailed requirements of the standard, as well as more time performing the required inspection. This option should have a similar, although somewhat smaller, impact on California jobs, as compared to option one.

Leakage Measurement Incentives. The third option, that of rewarding reduced leakage levels that have been verified by measurement, combined with some prescriptive limitations on the materials and techniques used to achieve these leakage levels, may or may not save any energy for California. The savings may not materialize both because it is possible that no one will elect to exercise this option (i.e., energy-savings credits for duct leakage measurement), and because the savings obtained could be traded off against other energy-savings options in the standard. However, if the energy budget for the base-case house is kept constant, and the default duct efficiencies are adjusted as discussed above, the only problem would be education to assure that this option is exercised. Another point worth mentioning is that providing such a carrot may pave the way for required measurements in the future. Moreover, analyses performed to date suggest that duct sealing should be an attractive option for builders, as it is expected to cost less per unit of energy savings, and not have any detrimental impacts on the marketability of the house (e.g., such as reduced glazing area).

Incentives for Prescriptive Packages. The fourth option, that of rewarding compliance with a detailed set of prescriptive requirements, may result in energy savings for the state of California, however this option could actually result in increased energy use. As with option three, savings could be realized by maintaining the same energy budget along with reduced default efficiencies. On the other hand, if the energy budget is revised along with the default duct efficiencies, this option could result in increased energy use. Specifically, if builders take credit for the efficiency gains associated with the prescriptive requirements, but building inspectors are unable to enforce compliance with those requirements, energy use would increase due to the fact that other energy-savings measures were not included in the buildings. Once again, a reward system could be used as a precursor to a requirement, however I personally feel that this is the weakest and least desirable of the four options.

For all four options, the alternative pathway of placing the entire duct system in the conditioned space is attractive in many ways, however there are some pitfalls that need to be carefully considered with this option. Specifically, the definition of conditioned space will have to be carefully crafted, and the addition of some measurement and/or prescriptive requirements is probably required. The additional requirements are necessitated by the fact that spaces which appear to be conditioned have been found to communicate with the outdoors or unconditioned spaces at an unacceptable frequency. As an example, the space between the first and second stories has been found to communicate with the outside at the band joists, or with unconditioned attics in split-level houses. It is of course possible to include additional efficiency credits within this pathway based upon measurements or prescriptive specifications.

Another consideration relative to the treatment of conditioned-space ductwork in Title 24 is that the present standard does not give any credit for installing a fraction of the ductwork in the conditioned space. More specifically, the present interpretation by the CEC effectively does not allow any credits for conditioned-space ductwork unless a condensing furnace is installed. This stems from the fact that the credit is only allowed if the ductwork and air-handler are entirely within the conditioned space, a scenario that is only possible with condensing furnaces. As a result, because of the high incremental cost of condensing furnaces, virtually nobody is taking the conditioned-space ductwork credit. It seems to make sense to devise some methodology that reduces the credit based upon the surface-area of the duct system that is outside the conditioned space.

Non-Energy Benefits of Reduced Duct Leakage. It is worth pointing out that there are a number of non-energy benefits associated with installing more airtight ductwork in California houses. In addition to the indoor air quality issues discussed above, at least one study indicated an improvement in thermal comfort associated with improving duct system efficiency [Modera and Jump 1995]. In that study it was shown that the temperature of the air leaving the registers was improved (i.e. made closer to that at the plenum, and made more uniform between registers) after the duct system was sealed and insulated. Some of that improvement is clearly due to the insulation, however some was clearly due to reductions in return leakage, and the associated improvements in return-plenum temperatures.

Recommended Strategy for Title-24

Based upon our analyses of duct leakage and efficiency issues for the Title-24 energy efficiency standards, we would propose a three-pronged modification of the current treatment of ducts in the present Title-24 compliance procedures. This includes: 1) changing the assumed duct efficiencies in the standards to reflect the present understanding of those efficiencies, 2) make duct leakage testing and some prescriptive requirements for sealing materials a part of the standard, and 3) create some flexibility in the treatment of conditioned-space ductwork in the standard.

In light of the success of the simplified diagnostic procedure tested as a part of the field study, it seems to be technically and practically feasible to enforce a fairly strict requirement for duct leakage levels in new construction. This protocol could be used by building inspectors, whose interest in actually performing this service could be garnered because of the health and safety issues discussed above. If this protocol is specified, it should probably be used on a pass/fail basis with the limit chosen so as to safely accommodate the uncertainties in the technique, and should simply require the building inspector to check whether the house pressures for the test are within clearly specified limits (i.e., make the inspector's job as easy as possible).

On the other hand, it may make more sense for duct leakage testing to be performed in a manner similar to that used for testing of plumbing vents and gas lines. This latter strategy would imply that the contractor prepare a duct leakage check for the inspector to examine. The protocol, which should be very similar to that in Modera 1990, would involve the use of a duct blaster, and would be performed when the system is installed (i.e., when all the leaks are accessible, thereby making it much easier to pass). One interesting anecdote relative to this procedure is that the duct registers located on the floor are apparently sealed on a regular basis during construction so as to minimize the collection of construction dust and debris in the ductwork. This would make the leakage test very inexpensive to perform, as most of the time associated with the test is taken up sealing the registers.

Should the specification of required duct-leakage testing in the next revision of the Title-24 compliance procedures prove to be unfeasible for any reason, duct leakage testing should at the very least be included as an option that will result in energy efficiency credits, and be required of any builder taking credit for the improved energy efficiency of variable-capacity equipment.

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